Refined Source Terms in WAVEWATCH III with Wave Breaking and Sea Spray Forecasts

Michael L. Banner
School of Mathematics and Statistics
The University of New South Wales
Sydney 2052, Australia
Tel : (+61) 2 9385 7064 fax: (+61) 2 9385 7123 email: m.banner@unsw.edu.au

Russel P. Morison
School of Mathematics and Statistics
The University of New South Wales
Sydney 2052, Australia
Tel : (+61) 2 9385 7064 fax: (+61) 2 9385 7123 email: r.morison@unsw.edu.au

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LONG-TERM GOALS

Several U.S. Federal Agencies operate wind wave prediction models for a variety of mission specific purposes. Much of the basic science contained in the physics core of these models is over a decade old, and incorporating recent research advances over the last decade will significantly upgrade the model physics. A major goal is to produce a refined set of source and sink terms for the wind input, dissipation and breaking, nonlinear wave-wave interaction, bottom friction, wave-mud interaction, wave-current interaction as well as sea spray flux. These should perform demonstrably better across a range of environments and conditions than existing packages and include a seamless transition from deep to shallow water outside the surf zone. After careful testing within a comprehensive suite of test bed cases, these refined source terms will be incorporated into the prediction systems operated by these agencies and by the broader wave modelling community.

OBJECTIVES

Our aim to improve the accuracy of ocean wave forecasts over a wide dynamic range of wind speeds out to hurricane conditions, contributing a dissipation source function that adds explicit wave breaking statistics for the wind sea to the forecast products. Allied aims are to effectively decouple swell systems from the wind sea and to provide a framework that allows full coupling to the associated atmospheric and ocean circulation models. As part of this project we aim to refine the parameterization of air-sea and upper ocean fluxes, including wind input and sea spray as well as dissipation, and hence improve marine weather forecasts, particularly in severe conditions.

APPROACH

We have continued using our refined version of the threshold-based spectral dissipation rate source term S_{ds} introduced by Alves and Banner (2003), as described in detail by Banner and Morison (2010).

This replaces the original Komen-Hasselmann integral formulation for S_{ds} presently used in most operational models. The performance of this updated source term was investigated in conjunction with a modified Janssen (1991) wind input source term and the 'exact' form of the nonlinear source term S_{nl} (Tracy and Resio, 1982) over a very wide range of wind speeds using a broad computational bandwidth for the wave spectrum. This avoided the known spurious effects arising in faster approximate versions for this source term.

A significant issue is the additional wind stress component due to the separated air flow over breaking waves. Our methodology produces breaking wave stress parameterizations linked to computed breaking wave properties, and indicates that this additional wind stress component can be an appreciable fraction of the total wind stress depending on the wind speed and wave age conditions, consistent with observations of Banner (1990). In hurricanes, our calculations suggest it can approach around one third of the non-breaking wave stress.

Detailed comparisons have already been made with growing wind sea results from the ONR FAIRS open ocean data set (e.g. Edson et al., 2004) gathered from FLIP in 2000. Here, breaking wave observations that were made along with measurements of wind stress, wave height and water-side dissipation rate. Our model results closely reproduced these observations, including the breaking wave properties. We have also tested our model framework over the wind speed range of 3-100 m/s and found the model behaved stably and has produced plausible results for both wave and sea surface drag coefficient behaviour.

Our model framework has been transitioned into the WaveWatch III environment, using the Exact NL, and DIA options for the nonlinear source term S_{nl} in our model refinement. During the next 12 months we expect to use other implementations of S_{nl} as they become available.

WORK COMPLETED

During FY15, as a result of newly published open ocean breaking wave and wave boundary layer observations, we extended our study on the impact of refining our wave evolution source terms. We were especially interested in investigating what controls the modeled directional spreading width in the spectral tail, and how to increase the accuracy of forecast breaking wave properties.

A key focus of our effort was investigating the performance of the FY15 refinement of our dissipation (S_{ds}) and wind input (S_{in}) source terms against the comprehensive data set for very young wind seas reported by Schwendeman et al. (2014) and for the open ocean cases reported by Sutherland and Melville (2015). These verifications were carried out with our research fetch/duration limited model that utilizes the 'Exact NL' formulation for the nonlinear spectral transfer term S_{nl}.

In parallel, our source terms have been implemented in WaveWatch III. We have been assessing their performance against a number of criteria, including significant wave height, wave periods, wave train evolution, breaking wave probabilities, spectral crest length per unit area distributions, and others. One of the key validation properties we are also examining is the drag coefficient, and how it behaves as a function of U_{10}, sea state and other conditions in both the model and the available data. For the latter, we are using NCEP's Climate Forecast System Reanalysis Version 2 (http://cfs.ncep.noaa.gov/cfsv2.info/CFSv2_paper.pdf/). A detailed publication describing the refinements to our source terms and their performance is in preparation.

RESULTS

In FY15, new papers appeared in the literature that allowed a more critical evaluation of our S_{ds} source term and our spectral breaking wave extraction methodology. New upper ocean TKE dissipation rate data and broader spectral bandwidth breaker crest length densities were reported for a range of wave age conditions. On this basis, we decided to revisit our source term parameterizations for wind input and dissipation at high wavenumbers. The model refinements made during FY15 and their outcomes are summarized below:

(i) *source term refinement at high wavenumbers*

In the context of the Banner and Morison (2010) model framework, the input source term was modified to have a u_* sheltering exponent set to 0.95 and the main coefficient was reduced to 1.2. The dissipation source term had its tail exponent reduced from 4 to 2, and the main coefficient was increased to 7. Using these settings, we investigated again the performance of our refined source terms for wave dissipation and wind input integrated over the spectrum against the observed terms during the young wind sea growth episode in the Strait of Juan de Fuca reported by Schwendeman et al. (2014). We compared the fetch evolution of our modeled integrated S_{in} and S_{ds} source terms with those observed and the computed versus observed significant wave height H_s. The close correspondence of the results with these refinements remained very reassuring.

(ii) *angular spreading dependence in the wind input: implications for directional spreading*

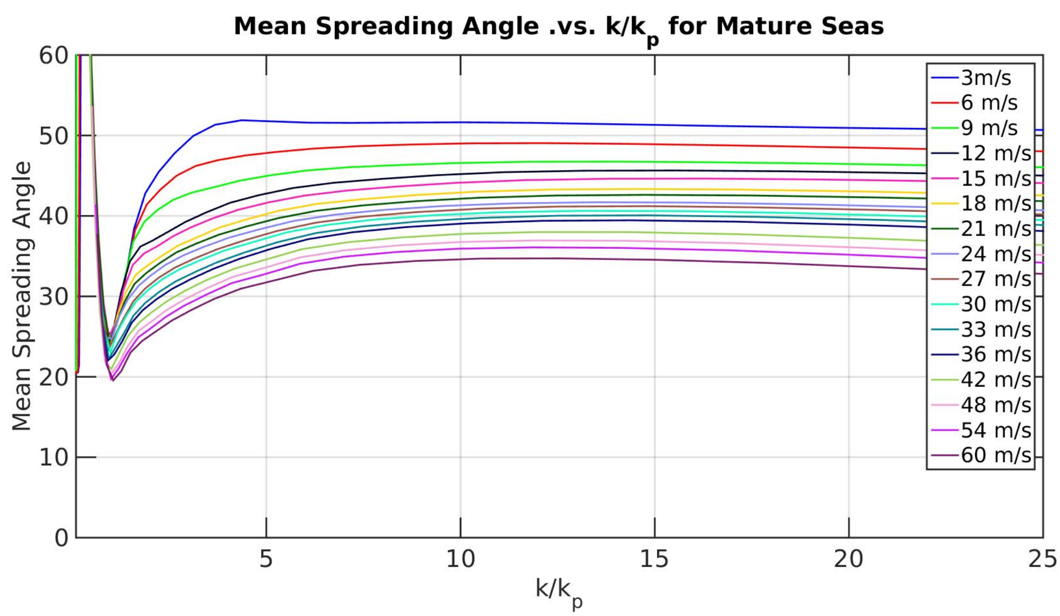

Figure 1. Mean spreading angle for old seas for wind speeds 3 m/s to 60 m/s. The wave age $c_p/u*$ was approximately 28.

As pointed out in our FY14 report, the standard Janssen (1991) wind input source term has the input dependent on $(u_* \cos\theta)^2$, yet the directionally-resolved wind stress has a $u_*^2 \cos\theta$ dependence. With this in mind, we modified the directional dependence of the wind input source term S_{in} from $\cos^2\theta$ to $\cos\theta$. This produced an increase of about 10 degrees in the total directional spreading width of the spectral

tail. This brings the modeled directional spreading width into closer agreement with the limited available observations. We note that WaveWatch III uses the DIA form in S_{nl}, which has an intrinsically broader spreading width than Exact NL. This produces broader direction spreading in the spectral tail in closer agreement with observations.

With the revised tail source term balance and the cosθ wind input directional dependence, the half width directional spectral angle is seen in Figure 1 to be within 40-55 degrees depending on wind speed. Similar calculations at different wave ages show that a strong wave age dependence is operative as well.

(iii) *refinements for breaking probability against normalized saturation.*

We obtained access to two new field measurement datasets for young wind sea conditions, from locations in the Strait of Juan de Fuca and in the Adriatic Sea. By combining these new data with our existing breaking observations, we refined the dependence of the breaking probability on the directionally-normalized wave saturation introduced by Banner et al. (2002). We replaced the linear dependence with a half-power dependence, as indicated in Figure 2. This provides forecast breaking probability estimates that agree more closely with the new observations for very young seas, as well as for higher wind sea states and older seas available from previous field data.

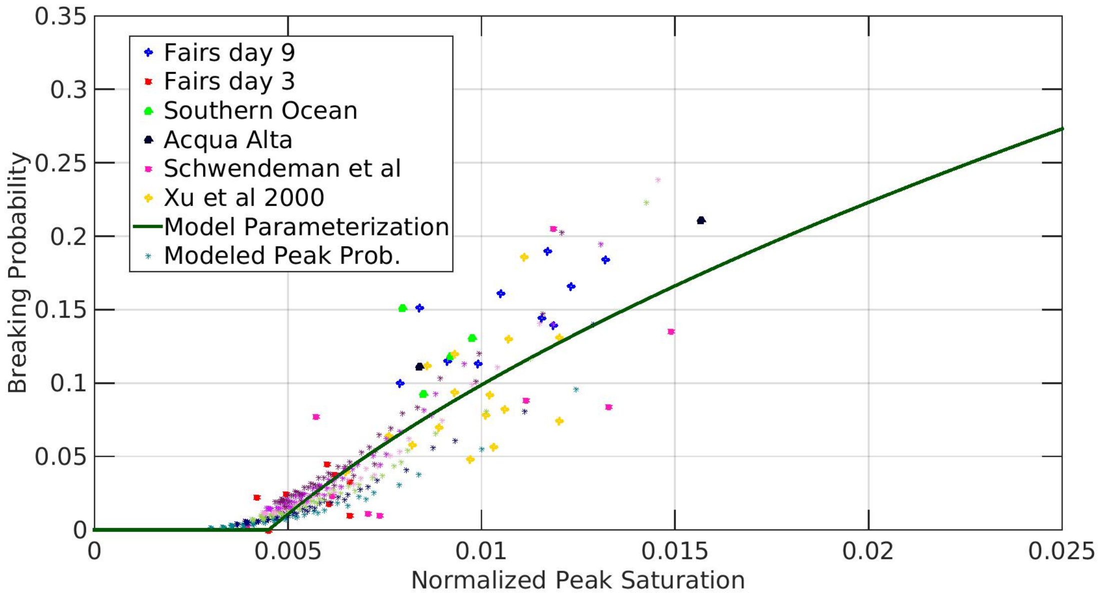

Figure 1. Measured and parameterized breaking probability for the spectral peak waves as a function of the directionally-normalized spectral peak saturation. The large symbols show available spectral peak breaking probability data for different experiments. The magenta line is the square-root dependence now used in our model. The small colored asterisks * are for the breaking probability calculated from the model, by integrating from 0.7 to 1.3f_p c* Λ(c) dc.

In addition to improving the accuracy of breaking probability forecasts, refining the breaking probability formulation modifies the dissipation rate and wind input source terms, which influences the wave model outputs.

(iv) refinements to modeled wave breaking properties

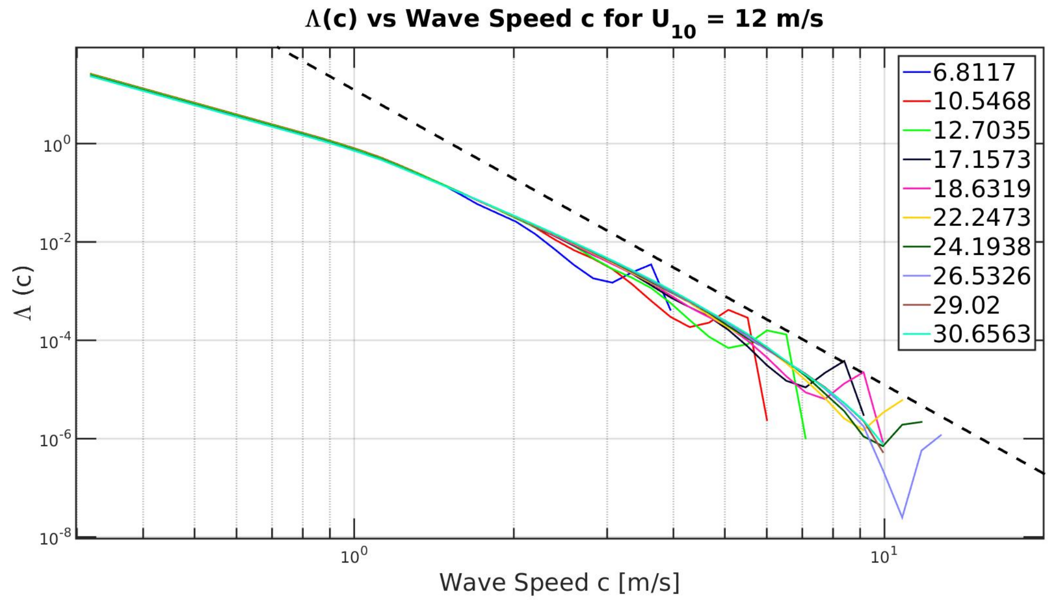

Figure 3. Modeled Λ(c) against wave speed c for U_{10}=12 m/s for different wave age c_p/u_*. The dashed line shows the c^{-6} dependence predicted by Phillips (1985) equilibrium range model.

Sullivan and Melville (2013, 2015) reported Λ(c) measurements which closely follow a c^{-6} curve for wave speeds down to around 2 m/s, using stereo infrared cameras mounted on FLIP. By reformulating the spectral dependence of the input and dissipation source terms, and formulating the breaking strength b(k) in terms of the square root of the normalised saturation above a threshold, the Λ(k) values are obtained from the modeled breaking dissipation $S_{ds}(k)$ and breaking strength b(k) using the equation below derived by Phillips (1985):

$$\Lambda(k) = \frac{g\,S_{ds}(k)}{b(k)\,c^5}$$

Our modeled Λ(c) distributions shown in Figure 3 follow a very similar dependence to the Sutherland and Melville observations to about 1-2 m/s. The observed data suffers resolution issues at around this value, and so the modeled and observed data differ below 2m/s.

From our refined model source terms, we post-processed the S_{ds} results to recover the Phillips (1985) spectral breaking measures: spectral density of breaker crest length per unit area Λ(k) and breaking strength b(k). Present breaking wave measurements, including those made in the Strait of Juan de Fuca field experiment, provide Λ(c) and the spectrally-integrated breaking strength b_{eff}, which is defined (Gemmrich et al., 2013) by

$$\int S_{ds}(c)\,dc = b_{eff} \int c^5\,\Lambda(c)/g\,dc$$

Figure 4 shows the modeled behavior of b_{eff} with wave age for a wide range of wind speeds, which include those during the Strait of Juan de Fuca field experiment. The model predicts a modest decrease in b_{eff} as the seas age. The modeled results show levels consistent with those observed by

Schwendeman et al. (2014, figs. 10 and 11) as well as Sutherland and Melville (2015) which show b_{eff} ~ O(10^{-3}).

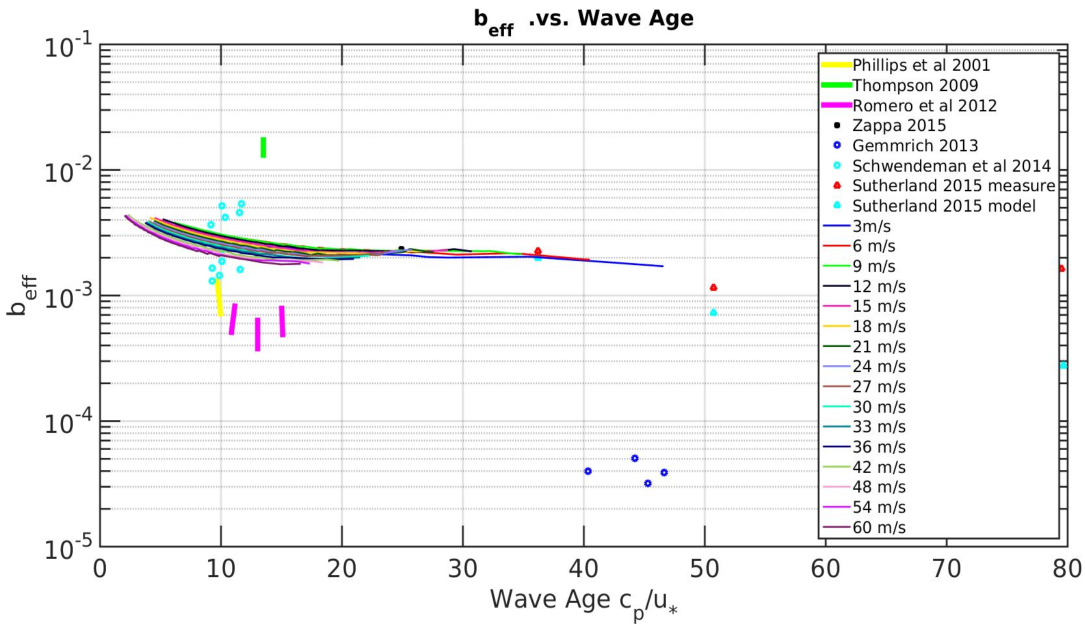

Figure 4. Modeled behavior of spectrally-integrated breaking strength b_{eff} against wave age c_p/u_* for a wide range of wind speeds. These model results indicate that b_{eff} is relatively insensitive to the absolute wind speed and decreases only modestly with wave age.

IMPACTS and APPLICATIONS

This effort will contribute significantly to the major NOPP goal of upgrading the model physics for wind-generated ocean waves, the near-surface winds and upper ocean circulation in the WaveWatch III model environment. The upgraded WaveWatch III model code will be distributed to various Federal agencies for incorporation in their mission-specific systems. The major impact will be more accurate and comprehensive sea state and marine meteorological forecasts from the next generation of operational sea state models.

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